Effects of Heterogeneity on the Performance of Pocket Switched Networks

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Abstract

Pocket Switched Networks (PSNs), which are formed by mobile devices carried by their users, present an interesting communication paradigm especially in the absence of access to global network connectivity. This work explores the effect of nodes' heterogeneity on the performance of PSNs that use opportunistic communication mechanisms. The focus is on the diversities reflected by the hardware (specifically, buffer size and network interfaces) and software (specifically, routing protocol) of the nodes. Further, the effects of the asymmetric (unidirectional) connections among the devices have also been studied. While there could be other forms of diversities, for example, different MAC layer protocols, the ones considered here are among the fundamental, and have the potential to render available communication opportunities useless. We use time-varying graphs to represent a PSN with heterogeneous routing protocols and capture its effect. To address the interactions among diverse routing protocols, the use of special nodes, Protocol Translation Units (PTUs), is proposed. Each PTU runs a hybrid routing protocol, which encapsulates the functionality of two or more routing protocols. The results of performance evaluations reflect that deploying PTUs promotes the delivery ratio of the messages by about $15\%-50\%$, compared to the levels obtained in, otherwise, homogeneous PSNs.

I. INTRODUCTION

PSN [1] is a category of Delay-Tolerant Networks (DTNs) where the portable devices carried by the human beings, for example, mobile phones and PDAs, form a network among themselves. These devices use global network connectivities, when available, for communications. PSNs, however, present an interesting and useful mechanism supporting communication in the absence of any network infrastructure. Under such a scenario, the devices in PSNs engage in opportunistic communications with the other devices when they are in the transmission range of one another.

A. Motivation

Various aspects – such as, routing [2]–[4], security [5] and cooperation [6] – related to the PSNs, or DTNs in general, have been explored by the research community. The existing works, however, have addressed scenarios where the network compositions are homogeneous. Such an assumption, however, may not hold true in real life. To illustrate, two end devices cannot communicate with each other using incompatible network interfaces, such as Bluetooth and Wi-Fi adapters. Further, communication between two devices in a PSN running different routing protocols may fail due to incompatibility of the
routing protocols. These issues, if not addressed, would affect the performance of spontaneously formed PSNs. Moreover, such heterogeneity would adversely affect the performance in MOONS [7] – an extension of the PSNs considering the mission objectives and influence of the human owners upon the network communication process. In [7], the authors considered how intuitive for of human intelligence increases zone visits in a post-disaster rescue scenario. A MOON formed in such a scenario with the objective of maximizing message transfer would be affected due to heterogeneity.

In this work, the effects of nodes’ heterogeneity, reflected by their hardware and software, on the performance of PSNs using opportunistic communications have been considered. On the hardware aspects, specifically, the asymmetric (unidirectional) connections, buffer sizes, and incompatible network interfaces of the mobile devices have been considered. The work also explores the diversity in the software of the devices by considering them running different routing protocols. To address such diversity, the use of special nodes, Protocol Translation Units (PTUs), have been proposed. Each PTU runs a hybrid routing protocol, which encapsulates the functionalities of two or more routing protocols. The question about the availability of the PTUs in real-life PSNs can be addressed by considering that a certain fraction of the users already possess such devices. This is possible either when the users purchase such devices, or are promoted by some person/organization.

B. Contributions

The specific contributions of this work are summarized as follows:

• Acquiring insights on – and evaluating – the effect of diversity in hardware (specifically, buffer size and network interfaces) of the devices on the network performance.
• Investigating the interaction of different routing protocols and the resulting performance degradation in the network.
• Using time-varying graphs (TVGs) [8] to represent a heterogeneous PSN, and defining communication degree to capture the effects of diverse routing protocols.
• Proposing the use of PTUs, which use hybrid routing protocols, to counter such degradation.

II. RELATED WORK

The issue of heterogeneity in the context of ubiquitous and pervasive computing has been widely addressed in the literature. Schmohl and Baumgarten [9] noted that heterogeneity arises in mobile computing environments due to the hardware and software of the devices, and the architecture of the network. Bromberg et al. [10] proposed the Starlink framework – a middleware for run-time bridging of heterogeneous protocols. The proposed framework can address heterogeneity related to the different message formats and protocol’s behaviour. Heterogeneity often arises due to diverse link layer protocols for example, MAC protocols based on/or not cognitive radio [11]. Stuedi and Alonso [12] explored the integration of heterogeneous MAC protocols in mobile ad hoc networks, with specific focus on 802.11 and Bluetooth. The authors proposed the use of software-based virtual interface to integrate the devices with different MAC layers. The proposed approach, although novel, is suitable for traditional networks using end-to-end communication paradigms. Moreover, the assumption of the use of such bridging software may further lead towards heterogeneity.

The unlayered architecture of Haggle [13] was developed for the PSNs. Haggle’s focus is on data-centric networks, and is located in between the application layer and the hardware interfaces. Petz et al. [14] presented MaDMAN, a middleware
for dynamic switching between MANET and DTN protocols. In their proposed architecture, the network stack consisted of a collection of different possible transport, network and link layer protocols. The network stack could be switched with another even while the application is running, which enabled communications with asymmetric protocols. While no comparative performance of the two models are available, MaDMAN supports more extensibility. However, unlike Haggle, MaDMAN does not support data transfer with user-level naming.

Lee and Eun [15] and Tian and Li [16] considered the heterogeneity in the contact process of the mobile nodes and diversity in the pairwise contact patterns. Such factors, however, do not reflect the heterogeneity in the composition of the concerned networks. Li et al. [17] explored deploying defense mechanisms in PSNs to prevent malware attacks. The authors considered a network of heterogeneous devices, where different types of malware can only attack the systems they are targeted for. Manam et al. [18] presented the performance modeling of two routing protocols (two-hop and Epidemic) by considering the nodes to have heterogeneous transmission ranges. The delivery latency of the messages was found to decrease with the increasing transmission ranges of the nodes.

It may be noted that, apart from the diversities in the mobility patterns and contact dynamics, there are several other factors that lead to a heterogeneous network. A walk through of the existing works reveal that there is a lack of comprehensive approach to address the heterogeneity, and its impacts, on PSNs, or DTNs, in general. Besides, while works in [15], [16], [18] focus on the reduction of communication opportunities in the network, heterogeneity of certain aspects (e.g., incompatible network devices – in absence of any bridging [12], and routing protocols) turn available communication opportunities useless. Further, the existing works do not present any insight, in terms of quantitative values, on how performance degrades in heterogeneous PSNs. In this work, through extensive simulations, such degradation in the PSNs, and the improvements obtained in the presence of interoperability mechanisms, have been quantified.

III. HETEROGENEITY IN PSNS

This Section presents the various aspects that contribute to heterogeneity in a PSN.

A. Heterogeneity in Connection Dynamics

Heterogeneity in the connection dynamics of the devices arises due to one or more of the following reasons: 1) Asymmetric transmission ranges and/or speeds, 2) Diversity in the link-layer protocols of the devices, and 3) Asymmetric device scanning intervals.

Diverse transmission ranges could result in one-way connectivity between a pair of devices. Further, each device scans for its neighbours periodically after a certain time interval. Devices with variable scan intervals would affect the frequency of neighbour discovery, and, hence, possibly decreased number of connection establishment events. Such issues, however, could be induced by the underlying link-layer protocol of the devices, and their further consideration have been scoped out in this work.
B. Diverse Hardware of the Devices

Users’ devices have a fixed buffer size, which determines how many messages could be stored by a device at any given time. Another potential hardware related issue is the presence of incompatible devices in the network. For example, let us consider two devices where the first has a Bluetooth interface, while the other has a Wi-Fi interface. Such devices, although may be within the transmission range of each other, cannot communicate due to their differences in the network interfaces.

C. Routing Protocols in DTN and their Compatibility

To discount the effects of intermittent connectivities, several routing schemes based on message replication have been adopted. The simplest scheme in this case is the Epidemic routing \[19\], where every node replicates and forwards the messages they are carrying to the nodes not having the messages’ copies. SnW \[3\], on the other hand, limits the maximum number of replication possible in the network. For each message generated, SnW assigns a count \(L > 1\). Any node having a copy of the message forwards a copy to another node as long as \(L > 1\). After forwarding, it reduces its own count of copies to \(L/2\) or \(L - 1\), depending on whether the protocol is run under binary mode or not.

In PROPHET \[2\], a node forwards a replica of a message to another node only if the other node has greater chances of encountering the destination of the message than itself. The following equations govern the functionality of PROPHET:

\[
\begin{align*}
P_{(a,b)} &= P_{(a,b)\text{old}} + (1 - P_{(a,b)\text{old}}) \times P_{\text{init}} \\
P_{(a,b)} &= P_{(a,b)\text{old}} \times \gamma^k \\
P_{(a,c)} &= P_{(a,c)\text{old}} + (1 - P_{(a,c)\text{old}}) \times P_{(a,b)} \times P_{(b,c)} \times \beta
\end{align*}
\]

Here, \(P_{(a,b)}\) and \(P_{(a,b)\text{old}}\), respectively, indicate the current and previous delivery predictabilities, i.e., the likelihood that any node \(a\) would meet with another node \(b\); \(P_{(a,b)} \in [0, 1]\); \(P_{\text{init}} \in [0, 1]\) is an initialization constant. The delivery predictabilities are aged with time when two nodes do not encounter for long. The parameter \(\gamma \in [0, 1]\) is the aging constant, and \(k\) denotes the number of time units expired since the last update of this predictability. The scaling parameter \(\beta \in [0, 1]\) controls extent to which transitivity should affect the delivery predictability.

Although these routing protocols help in enhancing the message delivery ratio, most of the protocols are not compatible with one another primarily due to two reasons:

- The protocol-specific headers added to the messages while they are created, and
- The operation modes of the protocols, for example, single- or multi-copy routing and message forwarding/replication criteria.

Further, routing in content-centric DTNs often do not have a particular destination address \[20\], unlike the traditional routing protocols.

D. Effects of Incompatibilities

Lack of interoperability among the devices results in the following adverse effects in PSNs:
• **Loss of communication opportunities**: Devices cannot communicate even when they are near to each other, i.e., communication opportunities are lost.
• **Undelivered messages**: Certain messages in the network always remain undelivered, no matter what resource and time are provided.
• **Increased delivery latencies**: Nodes have less communication opportunities, which affects, on an average, the time required to deliver the messages.

Thus, it is desirable that such issues are addressed to achieve better performance in the network.

### IV. REPRESENTATION OF HETEROGENEOUS PSNS

Casteigs *et al.* [8] presented the concept of TVGs as $G = (V, E, \tau, \rho, \zeta)$, where $V$ is the set of nodes, $E$ is the set of edges, and $\tau$ is the lifetime of the system. $\rho$ is called the presence function indicating the existence of a particular edge at a given time, and is represented as $\rho : E \times \tau \rightarrow \{0, 1\}$. The function $\zeta$ represents the (possibly time-varying) latency involved to travel an edge from one end point to the other.

The above TVG model could be used to represent a heterogeneous PSN. In particular, $\rho$ accounts for multiple scenarios of heterogeneity, for example, devices with incompatible network interfaces and asymmetric connection events. However, since $\rho$ indicates the temporal presence of the links, it cannot capture the scenarios when a link exists, but no communication is possible, such as when diverse routing protocols are used.

Let, $E_\tau$ be the set of the edges that exists over the entire network lifetime, i.e., $E_\tau = \{e \in E : \rho(e,t) = 1, t \in \tau\}$. Let us define a function $\phi$ such that $\phi(e \in E_\tau) = 1$, if the nodes at the two end points of the edge have compatible routing protocol, and 0, otherwise. Therefore, $E_C = \bigcup_{e \in E_\tau} \phi(e) \subseteq E_\tau$ gives the set of potentially communicable edges in the network i.e., the edges through which messages could be exchanged. A measure of $\alpha = \frac{|E_C|}{|E_\tau|}$ indicates the communication degree of a PSN resulting due to the diverse routing protocols, and depends on the number of nodes in the PSN, routing protocols used by them, as well as their mobility patterns.

A logical question that arises here is – what role, if any, do the nodes play in a heterogeneous PSN when there is apparently a possibility of communication? By apparently, we mean that the link layer of a device indicates that it can communicate with another device. Even if such a link layer connectivity exists, several factors, for example, energy levels and routing protocols could prevent the actual communication. Let us consider the scenario when the messages sent by one node could not be interpreted by the other due to the difference in their protocols. In this case, however, both the nodes consume energy during transmission/reception of the messages. Such an issue could be circumvented if the link layers of the devices advertise the routing protocols used by them, and, therefore, do not engage in further communication if the other device is not found to use a compatible protocol.

### V. OVERCOMING THE ADVERSE EFFECTS OF NETWORK HETEROGENEITY

This Section explores how the adverse affects of heterogeneity could be mitigated. The approach presented here derives from the general concept of *bridges* discussed in [9].
A. Hardware Incompatibility

The capacity of existing PSNs with differing network interfaces could be easily augmented in the presence of devices that are accompanied with multiple types of network interfaces. For example, a group of devices having only Bluetooth adapters could be bridged to a group of devices having only Wi-Fi capabilities if they come in contact with one or more devices having both types of network interfaces.

This work considers two network interfaces – if1 and if2 – that are assumed to be incompatible with each other. It is considered that certain devices in the PSN have only either if1 or if2, and the remaining have both. Any device having if1 (if2) could communicate with other devices having if2 (if1) or both. Communication is not possible otherwise.

B. Protocol Translation Units

We addresses the incompatibility issues between two specific routing protocols: PROPHET and SnW. They are representative of two different categories of routing protocols used with PSNs/DTNs – routing with 1) Fixed number, and 2) Unlimited copies of the messages. Moreover, while SnW maintains the state of a message (L), PROPHET considers the state of connectivity among the nodes (P(a,b)). Although variations of these protocols have been proposed, the principles described here holds good for them as well.

To overcome the communication impairments caused due to heterogeneous routing protocols, the use of PTUs is proposed. PTUs are “special devices” that can interact with two or more routing protocols both in terms of interpretation of protocol-specific headers and sequence of interactions. The PTUs run a hybrid routing protocol, encapsulating the syntax and semantics of both PROPHET and SnW protocols. This enables a PTU to communicate with both types of routers. This could be further extended to encapsulate the logic of multiple other protocols.

1) How the PTUs Help?: To understand how the PTUs handle the dynamic scenarios arising in the PSNs, let us consider two devices X and Y using the routing protocols SnW and PROPHET, respectively. Although X cannot successfully send a message to Y, it can do so to a PTU device. The latter, in turn, helps in forwarding the message to Y directly or through other intermediate nodes using the PROPHET routing protocol.

It is considered that the devices periodically emit beacon signals, which also provides information about the routing protocol used by the respective devices. The PTUs are assumed to advertise both the routing protocols in their beacon messages. Thus, any device that is running PROPHET (SnW) initiates communication with other devices if the received beacons advertise the use of PROPHET (SnW). Figure 1 shows the interaction among the different routers and the PTUs. In the Figure, the PTU identifies the routing protocol of the other device, and behaves accordingly. The Figure also shows the failed interaction between a SnW and a PROPHET router.

Algorithm 1 presents the interaction logic between a PTU and any other device using the PROPHET routing protocol. At the beginning, all the deliverable messages (i.e., the messages destined for the other device) are transferred. In case any such message was received from a SnW router, the corresponding SnW headers are removed, and PROPHET headers are added before forwarding. Replication of the remaining messages take place in the following two phases:
1) In the first phase, all the messages received from the other PROPHET routers are replicated depending on the delivery predictabilities as shown in (1), (2) and (3).

2) Subsequently, any message received from the SnW routers are replicated, provided $L > 1$. This ensures that the last copy of the message is directly delivered to the destination node.

**Algorithm 1** Interaction of the PTUs with PROPHET routers

Require:
- All messages carried by the device

Ensure:
- Exchange new messages with the other device

1: for each directly deliverable message do:
2: if message has SnW or PTU header then
3: Remove the header.
4: Add PROPHET header.
5: end if
6: Forward the message.
7: end for
8: for msg in remaining messages do:
9: if msg does not have SnW header then
10: Replicate and send according to the (1), (2), and (3). ▷ PROPHET messages
11: end if
12: end for
13: for msg in messages do:
14: if msg has SnW header with $L > 1$ then
15: Update header with $L = L/2$.
16: Replicate, remove header and send. ▷ SnW messages
17: end if
18: end for

Algorithm 2 presents a similar logic of interaction between the PTUs and the SnW routers.

**Algorithm 2** Interaction of the PTUs with SnW routers

Require:
- All messages carried by the device

Ensure:
- Exchange new messages with the other device

1: for each directly deliverable message do:
2: if message has PROPHET or PTU header then
3: Remove the header.
4: Add SnW header with $L = 1$. ▷ SnW messages
5: end if
6: Forward the message.
7: end for
8: for msg in remaining messages do:
9: if msg does not have SnW header then
10: Replicate, add SnW header with $L$, and send. ▷ PROPHET messages
11: end if
12: end for
13: for msg in messages do:
14: if msg has SnW header with $L > 1$ then
15: Set $L = L/2$, replicate and send.
16: end if
17: end for

2) Time Complexity: Let us assume that $n$ messages are generated in the concerned PSN. Thus, a PTU can have at most $n$ messages in its buffer. It may be noted that in the Algorithm 1 a PTU can identify the directly deliverable messages in $O(n)$ time. Moreover, the actions such as, removing/updating message header and replicating/forwarding a message can be
performed in constant time. Therefore, the time complexity of the proposed algorithm becomes $O(n)$, which is true for the
Algorithm 2 as well.

VI. SIMULATION

This Section discusses the experimental setup used to simulate the effects of the above discussed diversities in PSNs.

A. Experimental Setup

The effects of heterogeneity in PSNs were evaluated using the ONE simulator [21]. Real-life connection traces of 78 nodes from the Infocom’06 data set [22] were used.

The first scenario explored the possible impacts of asymmetry in the connection dynamics of the devices. The connection “Up” events were considered to be uni-directional. The scenario was contrasted with the case when such events were bi-directional.

In the second scenario, the effect of the buffer sizes on the delivery ratio of the messages was considered while using the SnW, Random forwarding (single copy), PROPHET and Epidemic routing protocols. Next, the effects of limited energy of the devices on the performance of PSNs were analyzed. The typical energy consumption rates for Motorola Milestone (http://www.gsmarena.com/motorola_milestone-3001.php) were considered. In particular, the initial energy was taken to be 1400 mAh, 3.5 V, and transmission and scanning energies as 0.7 Joule and 2 Joule, respectively.

We investigated the effects of incompatible network interface of the devices. A fraction of nodes with two network interfaces, if1 and if2, were considered. Half of the other nodes used if1, while the remaining nodes had if2.

Next, we explored the interactions of two different routing protocols – PROPHET and SnW. A group of nodes were considered running as the PTUs, and varied their count from 0% to 50% in steps of 10%. In each case, half of the remaining nodes used PROPHET, while the other half used the SnW protocol.

In the final scenario, the variation in communication degree was explored. In the first case, we divided the 78 nodes into two groups. The first group contained the 10−50% of the nodes incremented in steps of 10%; the other group contained the remaining nodes. In the two other cases, we considered 5 and 10 nodes, respectively, to be the PTUs. The remaining 68 nodes were divided into two groups in a similar way.

Table I summarizes the other parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of messages, size</td>
<td>400, 50 KB to 1 MB</td>
</tr>
<tr>
<td>Message creation time</td>
<td>5 hour</td>
</tr>
<tr>
<td>Transmission speed, range</td>
<td>2 Mbps, 10 m</td>
</tr>
<tr>
<td>SnW settings</td>
<td>Binary mode, $L = 16$</td>
</tr>
<tr>
<td>PROPHET settings</td>
<td></td>
</tr>
<tr>
<td>Duration</td>
<td>12, 18, 24 hours</td>
</tr>
</tbody>
</table>
B. Performance Metrics

The performance was evaluated based on the following metrics:

- Delivery ratio of the messages ($\gamma$),
- Delivery ratio versus delivery latencies, and
- Overhead ratio ($\omega$).

The delivery ratio gives the fraction of the created messages that were delivered to the respective destinations. A measure of this metric evaluates the effectiveness of any message forwarding scheme. Let, $M$ and $M_d$, respectively, denote the number of messages created and delivered in the PSN. Further, let $M_f$ denote the number of messages forwarded in the network, $M_f \geq M_d$. Then, the delivery ratio of the messages is defined as: $\gamma = \frac{M_d}{M_f}$.

The overhead ratio is computed as: $\omega = \frac{M_f - M_d}{M_d}$. It determines the efficiency of any routing protocol.

A plot of the delivery ratio of the messages versus delivery latencies provides insights in understanding the different components of the delay associated with the delivered messages.

VII. Results

This Section presents the results of the simulations, and related analysis.

A. Effects of Heterogeneous Connection Events

Figure 2 shows the impact on message delivery ratio when (all) the nodes used the SnW and PROPHET routing protocols. The “true” and “false” cases indicate the scenarios whether the connection events were considered to be symmetric or not. It can be observed that, for the lesser durations of simulation (or low message density per unit time), the asymmetry in connection among the devices reduces the delivery ratio of the messages by $30 - 40\%$. When sufficient time is given (the 24-hour case), the ratio improves significantly.

B. Effects of Buffer Size

Figure 3 shows the message delivery ratio with different buffer sizes when SnW ($L = 32$), Random, PROPHET and Epidemic routing protocols were used. In Random routing, a node forwards any message it has to the first node that it comes in contact with. Figure 3(a) & (b) indicates that with a fixed limit on message replication, excess buffer space does not help. Otherwise, larger buffers enhance the delivery ratio (Figure 3(c) & (d)) due to the reason that during each communication opportunity, more number of nodes get a copy of a message.

Figure 4 plots the delivery ratio of the messages versus the delivery latencies. Figure 4 (a) presents the base case when devices had unlimited energy, while Figure 4 (b) corresponds to the case when the devices had limited energy. It could be observed that limited energy budgets significantly degrade the performance in, otherwise, homogeneous PSNs. Further, the diversity in initial energies of the devices worsens the delivery ratio (Figure 4(b)) compared to the scenario when all the nodes had the same initial energies (indicated by “Same” in the graph).
C. Impact of Incompatible Networking Devices

Figure 5(a) shows how the delivery ratio of the messages is affected when a fraction of the devices have network interface \( if2 \), while the others use \( if1 \). The 0% case represents the scenario when all the nodes had \( if1 \). It could be observed that the delivery ratio steadily decreases as long as 20% of the devices have incompatible network interfaces. This could be explained by considering the fact that all the nodes could be partitioned into two mutually exclusive groups based on their network interfaces. As the size of each such group increases, more number of the nodes fail to exchange the messages among themselves, which reduces the delivery ratio.

The impact on the message delivery ratio in the presence of the nodes with dual network interfaces is shown in Figure 5(b). A steady increase could be observed till 20% presence of such nodes. This is due to the reason that the remaining nodes with either \( if1 \) or \( if2 \) gets opportunities to transfer their messages to each other through the nodes with dual network interfaces.

D. Effects of Heterogeneous Routing Protocols

Figures 6(a) and (b) present the delivery ratio of the messages when different routing protocols were considered. In Figure 6(a), the plots labeled with “SnW (k hour)” denote the base case performances when all the nodes used the SnW routing protocol and the simulation duration was \( k \) hour. The plots with labels “PROPHET (k hour)” represent the scenarios when different fraction of the population (shown along the \( x \)-axis) used the PROPHET protocol. It could be observed that, in comparison to the base cases, when the fraction of the nodes using PROPHET protocol increases, the delivery ratio drastically decreases. Finally, the delivery ratio obtained with equivalent fraction of PTU nodes are shown. It could be observed that, while varying the fraction of PTUs from 10% to 50% in the network, the delivery ratio obtained is almost the same as the best cases considered. Further, the Figure indicates that a mere presence of 20% PTUs in the network greatly enhances the delivery ratio as compared to the scenarios when PROPHET protocol was used.

Figure 6(b) shows the performance when the nodes used the PROPHET routing protocol together with the nodes using different fractions of SNW and PTUs.

Figures 6(c) and (d) show the overhead while using different types of routing protocols together for simulation durations of 12 and 24 hours. It could be observed that, when all the nodes used the SnW routing protocol, the overhead ratio was the least (around 15%). This is due to the reason that SnW assigns a fixed upper limit on the number of possible replications of any message.

It could be further observed that the overhead largely increases in the presence of the PTUs. This behaviour could be explained from Algorithm 2 where the PTU replicates a message from a PROPHET router with \( L \) copies to a SnW router. In Figure 6(d), it could be observed that the overhead ratio remains the same when all the nodes use PROPHET or a mix of PROPHET and PTUs. This is accounted for the reason that the PTUs interact “normally” with the PROPHET routers without increasing any overhead.

The variation in the communication degree (\( \alpha \)) of the PSN is shown in Figure 7. It shows that with the increasing group sizes, \( \alpha \) sharply decreases. However, in the worst case when both the groups had equal number of nodes, the presence of 10 PTUs enhances \( \alpha \) by 12%.
VIII. Observations

The observations from Section [VII] are summarized in the following points:

- When the time window considered is small, for multi-copy message forwarding, the buffer size plays a significant role.
- Heterogeneous connection dynamics (the simplest case due to different transmission ranges) substantially reduces the delivery ratio of the messages.
- Hardware incompatibility arising due to incompatible network interfaces is hard to address particularly because, one may opt for software upgrade, but not for purchasing a new phone. Therefore, any contact opportunity with devices with multiple interfaces should be used to the best. This may require the routing protocols to use information available from the link-layer of the devices.
- For approaching reality, any new protocol or mechanism proposed should take energy consumption of the nodes into consideration.
- The performance degradation due to software-based incompatibility among the routing protocols is severe, but could be prevented. This does not require all the users to update their software. Rather, the presence of few “special” devices (for example, devices with middlewares, or the PTUs as proposed here) could boost the performance.

IX. Conclusion

PSNs present an interesting communication paradigm, especially in the absence of global network connectivities. The performance of the PSNs, however, could heavily degrade in the face of various diversities manifested by the hardware and software of the devices. In this work, the effects of such degradation have been quantified through extensive simulations. To counter the negative impacts of the heterogeneous routing protocols used by the devices, the use of PTUs has been proposed. The results of performance evaluation showed that the use of PTUs can elevate the message delivery ratio to the value obtained in a homogeneous network.

In future, it is intended to consider the other forms of diversities, including the interactions among the diverse PTUs. While multiple middleware architectures promise of universal interoperability, it is not clear whether deployment of such a “single platform” to all the devices is feasible. Under such a scenario, the use of devices supporting two or more protocols, which attempts to address heterogeneity in incremental steps, could be considered.

REFERENCES


Fig. 1: Interactions among different types of routing protocols.
Fig. 2: Effects of (a)symmetric connection events on the delivery ratio of the messages.
Fig. 3: Impact of buffer sizes using (a) SnW ($L = 32$), (b) Random, (c) PROPHET and (d) Epidemic routing.
Fig. 4: Delivery ratio versus delivery latencies of the delivered messages (a) without and (b) with energy constraints.
Fig. 5: Effect of different networking interfaces when: (a) Different percentage of the nodes had incompatible network interface \( if2 \), and (b) The nodes had dual network interfaces.
Fig. 6: Percentage of messages delivered in presence of different types of routing protocols together with (a) SnW and (b) PROPHET. Overhead ratio in presence of different types of routing protocols together with (c) SnW and (d) PROPHET.
Fig. 7: Communication degree with different percentage of nodes in the first group.